

# FLUX DENSITIES AND RADIO POLARIZATION CHARACTERISTICS OF TWO VELA-LIKE PULSARS

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## ABSTRACT

We report on dual-frequency radio polarimetry observations of two young, energetic pulsars, PSRs J0940–5428 and J1301–6305. These were among the first Vela-like pulsars discovered in the Parkes Multibeam survey. We conducted observations of these pulsars with the Australia Telescope Compact Array (ATCA) at center frequencies of 1384 and 2496 MHz using pulsar gating while preserving full Stokes parameters. After correcting for bandwidth depolarization, we have measured polarization characteristics, flux densities, and rotation measures for these pulsars. The spectral indices derived from the ATCA data are shallow but still consistent with values seen for pulsars of this type. The rotation measures for both pulsars are consistent with those reported recently using data from the Parkes telescope, and both pulsars have highly linearly polarized pulse profiles at both 1384 and 2496 MHz. Our results support a previously noted correlation between high degree of linear polarization, shallow spectral index, and large spin-down luminosity.

*Subject headings:* polarization — pulsars: individual (PSR J0940–5428, PSR J1301–6305)

## 1. INTRODUCTION

PSRs J0940–5428 and J1301–6305 were among the first pulsars discovered in the Parkes Multibeam survey (Manchester et al. 2001). Both pulsars have fast spin periods ( $P = 88$  and  $185$  ms, respectively), and both are young, with characteristic ages  $\tau_c \equiv P/2\dot{P}$  of 42 and 11 kyr, respectively. They also have large spin-down luminosities:  $\dot{E} \equiv 4\pi^2 I \dot{P}/P^3 = 1.9 \times 10^{36}$  and  $1.7 \times 10^{36}$  erg s<sup>−1</sup>, respectively (Manchester et al. 2001), where a moment of inertia of  $I = 10^{45}$  g cm<sup>2</sup> is assumed. These characteristics place them in the category of Vela-like pulsars, which are generally defined as fast-spinning pulsars having characteristic ages  $10 \lesssim \tau_c \lesssim 100$  kyr and spin-down luminosities  $\dot{E} \gtrsim 10^{36}$  erg s<sup>−1</sup> (e.g., Kramer et al. 2003).

The radio polarization properties of such pulsars are useful to measure for several reasons. Rotation measures (RMs) are used to probe Galactic magnetic fields (Han et al. 2006) and can support associations between young pulsars and radio supernova remnants (e.g., Crawford & Keim 2003; Caswell et al. 2004). Young, energetic pulsars generally show a higher degree of linear polarization than older and less energetic pulsars (von Hoensbroech et al. 1998), and their polarization fractions and phase-resolved polarization characteristics can be used to constrain the pulsar’s emission geometry (e.g., Lyne & Manchester 1988; Everett & Weisberg 2001; Johnston & Weisberg 2006). In a number of cases, young pulsars have been observed to have single-peaked pulse profiles that are wide and highly linearly polarized (e.g., Crawford, Manchester, & Kaspi 2001), which may indicate emission from only one part of a wider conal beam (Manchester 1996). Pulsars with these kinds of emission properties

also typically have shallow radio spectral indices (von Hoensbroech et al. 1998). In this paper we report on radio interferometric observations of PSRs J0940–5428 and J1301–6305 conducted with the Australia Telescope Compact Array (ATCA; Frater, Brooks, & Whiteoak 1992). Polarization information was recorded in these observations, and from these data we derive flux densities, spectral indices, RMs, and polarization properties for these two pulsars and discuss the results.

## 2. OBSERVATIONS AND DATA ANALYSIS

We observed PSRs J0940–5428 and J1301–6305 with the ATCA in August 1999, soon after their discovery in the Parkes Multibeam survey (Manchester et al. 2001). Each pulsar was observed in the 6D array configuration with the 6 km antenna, which provides the highest possible spatial resolution. The pulsars were observed simultaneously at center frequencies of 1384 and 2496 MHz, with a bandwidth of 128 MHz at each frequency. Table 1 presents the observing parameters and details. Pulsar gating was used during each observation (e.g., Stappers, Gaensler, & Johnston 1999), which preserved pulse phase information. The data were reduced with the MIRIAD software package.<sup>4</sup> After excision of internally generated radio frequency interference (RFI), 13 contiguous 8-MHz frequency channels remained which covered a total bandwidth of 104 MHz at each frequency. The data were then further edited and flagged for RFI. The pulse phase bins were appropriately phase-adjusted as a function of frequency channel to account for interstellar dispersion, after which the frequency channels were summed. Full Stokes parameters were recorded for each pulse phase bin during each observation. We measured flux densities at both frequencies using the UVFIT and PSRPLT routines in MIRIAD. In both techniques, the resulting uncertainty was added in quadrature to a 5% contribution from the flux calibration uncertainty, taken to be a conservative upper limit on the uncertainty for the flux calibrator, PKS 1934–638. At each frequency, a weighted mean of

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the two measured flux densities was then computed (see, e.g., Crawford (2000) for more details).

PSRPLT also produced Stokes parameters for each pulse phase bin. From these, we computed the linear and circular polarization of the pulsed emission as a fraction of the total pulsed intensity at both frequencies. Prior to doing this, however, an RM was determined for each pulsar using the channelized 1384-MHz data. A position angle (PA)  $\psi$  was computed at the pulsar's location for each frequency channel using Stokes  $Q$  and  $U$ , according to  $\psi = 1/2 \arctan(U/Q)$ , and a linear fit to the result was performed as a function of wavelength, according to  $\psi = \psi_0 + \text{RM} \lambda^2$  (see Figure 1). A linear polarization magnitude  $L$  was computed from  $L = (Q^2 + U^2)^{1/2}$ , which was then corrected for the positive contribution of receiver noise (see, e.g., Manchester, Han, & Qiao 1998; Crawford, Manchester, & Kaspi 2001; Crawford & Keim 2003). PSR J1301–6305 suffered from significant bandwidth depolarization owing to its large RM, and the reported linear polarization fraction in Table 3 for this pulsar has been corrected at both frequencies to account for this. Stokes  $V$  represents circular polarization, with positive values corresponding to left-circular polarization.

The effect of bandwidth depolarization was determined in the following way: PAs within a bandwidth  $\Delta f$  centered at a frequency  $f_0$  are spread out in angle owing to Faraday rotation. Within the bandwidth, the PAs span an angle  $\Delta\psi_s$  determined by

$$\Delta\psi_s = \frac{(1.8 \times 10^5) \Delta f \text{ RM}}{f_0^3} \quad (1)$$

where  $\Delta\psi_s$  and RM are measured in rad and  $\text{rad m}^{-2}$ , respectively, and the frequencies are in MHz. The sum of the PA vectors within the bandwidth produces a net magnitude which is smaller than the corresponding sum of aligned PAs, owing to partial cancellation. The measured linear polarization fraction is therefore underestimated relative to its true value. The ratio of these two magnitudes,  $R$ , is determined by

$$R = \left| \frac{\sin(\Delta\psi_s/2)}{(\Delta\psi_s/2)} \right| \quad (2)$$

where  $\Delta\psi_s$  is again in rad (and  $R \leq 1$ ). The measured linear polarization fraction can be multiplied by  $1/R$  to correct for this effect.

### 3. RESULTS AND DISCUSSION

#### 3.1. Flux Densities and Spectral Indices

We compared our 1384-MHz flux density measurements with those reported for these pulsars at 1400 MHz by Manchester et al. (2001) and Johnston & Weisberg (2006) using single-dish observations at Parkes (see Table 2). These measurements, along with our measurements at 2496 MHz and a measurement of PSR J0940–5428 at 3100 MHz by Johnston & Weisberg (2006), are plotted in Figure 2. Our 1384-MHz flux measurement for PSR J0940–5428 is significantly larger than the value measured by Manchester et al. (2001), but it is consistent with the value reported by Johnston & Weisberg (2006). Conversely, PSR J1301–6305 has a measured 1384-MHz flux density from ATCA gating which is identical to the

one measured by Manchester et al. (2001), but it is only about half of that measured by Johnston & Weisberg (2006). The difference in these measurements may be caused by telescope gain variations, RFI, or scintillation effects, all of which can affect pulsar flux measurements.

Using our ATCA flux density estimates at 1384 and 2496 MHz, we computed spectral indices for both pulsars (Table 2). The measured values of  $\alpha = -1.3 \pm 0.3$  and  $\alpha = -0.9 \pm 0.3$  (defined according to  $S \sim \nu^\alpha$ ) for PSRs J0940–5428 and J1301–6305, respectively, are both shallow relative to the mean value of  $-1.8 \pm 0.2$  for the known radio pulsar population (Maron et al. 2000), but they are still consistent with the observed spectral index distribution for known pulsars; both Figure 1 of Maron et al. (2000) and the public pulsar catalog (Manchester et al. 2005)<sup>5</sup> show that the shallow end of this distribution extends up to  $\sim 0.0$ . The public pulsar catalog (Manchester et al. 2005) lists only one pulsar which has a measured spectral index that is positive: PSR J1740+1000 has a value of  $+0.9 \pm 0.1$  measured between 0.4 and 1.4 GHz (McLaughlin et al. 2002). This is well above the distribution shown in Figure 1 of Maron et al. (2000) for pulsars with a single power law spectral index. This pulsar, like the ones studied here, is fast-spinning and energetic, with a spin period of 154 ms and a spin-down luminosity of  $2.3 \times 10^{35} \text{ erg s}^{-1}$ . Its characteristic age of 114 kyr places it near the age range for Vela-like pulsars. Pulsars with these characteristics (identified by von Hoensbroech et al. (1998) as the B1800–21 class of pulsars) can in some cases have high turnover frequencies ( $\gtrsim 1 \text{ GHz}$ ; see, e.g., Maron et al. (2000) and Kijak et al. (2007)). However, McLaughlin et al. (2002) suggest that the spectral index measurement for PSR J1740+1000 may suffer from contamination by interstellar scintillation (refractive scintillation in particular), which is uncorrelated between frequencies. Thus, although such pulsars are expected to have shallow spectral indices, they are not expected to have positive values, and the two pulsars studied here do indeed have shallow and negative spectral indices.

#### 3.2. Polarization Characteristics

Both pulsars are highly polarized at 1384 and 2496 MHz. The phase-resolved polarization profiles and PAs constructed from the ATCA data are shown at both frequencies in Figure 3, and the measured polarization fractions from these profiles are presented in Table 3.

High-resolution profiles of PSR J0940–5428 at 1369 and 3100 MHz presented by Johnston & Weisberg (2006) show that this pulsar has an asymmetric, double-peaked profile, with the leading peak being somewhat weaker than the trailing peak. The separation of these peaks is  $\sim 15^\circ$  of the pulse phase, which corresponds to less than two bins in our ATCA profiles (Figure 3). It is not surprising, therefore, that these peaks are not resolved in our profiles. However, a hint of the leading component may be visible at both frequencies in Figure 3, and it is highly polarized in each case. The measured linear polarization fractions are 69% and 86% for the pulsed emission at 1384 and 2496 MHz, respectively, with uncertainties as given (see Table 3). These values are qualitatively consistent with the polarization profiles presented

<sup>5</sup> <http://www.atnf.csiro.au/research/pulsar/psrcat>

by Johnston & Weisberg (2006), although they do not report measured polarization fractions with which to compare our numbers. It is clear from the profiles for PSR J0940–5428 shown here and by Johnston & Weisberg (2006) that the pulsar remains highly polarized across a range of frequencies.

PSR J1301–6305 has a wide profile at 1384 MHz (Figure 3), and when bandwidth depolarization is taken into consideration, the pulsar is  $\sim 100\%$  polarized at both frequencies (Table 3). A high-resolution polarization profile at 1375 MHz presented by Johnston & Weisberg (2006) is consistent with the high degree of polarization measured in our 1384-MHz data. Our 2496 MHz data indicates that this pulsar, like PSR J0940–5428, remains highly polarized at higher frequencies. Both PSR J0940–5428 and PSR J1301–6305 also fit a previously noted trend in which pulsars with large spin-down luminosities ( $\dot{E}$ ) have high linear polarization fractions at 1400 MHz (Figure 4; see also von Hoensbroech et al. 1998; Crawford, Manchester, & Kaspi 2001).

The phase-resolved PA data for each profile are also shown in Figure 3. The PAs are referenced with respect to celestial North, as is the usual convention. Although variation in the PAs can be seen as a function of pulse longitude in each case, the profile resolution is low. No constraints on the emission geometry are possible with these data using the rotating-vector model of Radhakrishnan & Cooke (1969). Johnston & Weisberg (2006) present an in-depth discussion about the general properties of young pulsars in the context of polarization measurements and identify some trends. Apart from the correlations previously mentioned, we also note that these two pulsars have relatively simple pulse profile morphologies, as seen for young pulsars more generally. The PAs also show no evidence of orthogonal mode changes, with the possible exception of PSR J0940–5428 at 2496 MHz (Figure 3). There is no corresponding profile for PSR J0940–5428 at this frequency in Johnston & Weisberg (2006), but their 3100-MHz profile shows no indication of such a jump.

### 3.3. Rotation Measures

An RM was measured for each pulsar using the 1384-MHz data, and these RMs are reported in Table 3. A correction for the ionospheric contribution to the RM was not made, but this contribution is expected to be only a few  $\text{rad m}^{-2}$ , significantly smaller than the uncertainties in the measured RMs (cf. Johnston & Weisberg 2006 and references therein). The measured values from the ATCA data are consistent with the RMs reported recently by Han et al. (2006) and Johnston & Weisberg (2006) using observations at Parkes. Using the dispersion measures (DMs) reported by Manchester et al. (2001) and the measured RMs from our ATCA observations, the mean line-of-sight magnetic field strength was calculated for each pulsar according to  $\langle B_{\parallel} \rangle = 1.232 \text{ RM/DM}$  (Manchester & Taylor 1977). Here the RM and DM are in units of  $\text{rad m}^{-2}$  and  $\text{pc cm}^{-3}$ , respectively, and  $\langle B_{\parallel} \rangle$  is in  $\mu\text{G}$ . Table 3 lists the calculated values of  $\langle B_{\parallel} \rangle$ .

We compared published RMs of pulsars within a few

degrees of PSRs J0940–5428 and J1301–6305 with our measured RMs to see if the values were in any way anomalous. The 7 known pulsars that lie within  $3^\circ$  of the location of PSR J0940–5428 (at Galactic longitude  $l = 277.5^\circ$  and latitude  $b = -1.3^\circ$ ) which have measured RMs span DM values from  $\sim 100$  to  $\sim 200 \text{ pc cm}^{-3}$ . The derived values of  $\langle B_{\parallel} \rangle$  for these pulsars are scattered around zero, and  $\langle B_{\parallel} \rangle$  for PSR J0940–5428 (which has a DM of  $136 \text{ pc cm}^{-3}$ ) is consistent with this distribution. For the 9 known pulsars lying within  $3^\circ$  of PSR J1301–6305 (located at  $l = 304.1^\circ$ ,  $b = -0.2^\circ$ ) that have measured RMs, there is a large range of DM values ( $\sim 100$  to  $\sim 700 \text{ pc cm}^{-3}$ ), with the RM values trending toward large negative values as the DM increases. This is shown in Figure 6 of Han et al. (2006), which depicts RM as a function of both distance and DM for pulsars in the direction of the Crux spiral arm of the Galaxy. PSR J1301–6305 falls roughly in the middle of this DM range ( $374 \text{ pc cm}^{-3}$ ) and indeed has a large negative RM. In fact, its RM is the largest in the negative direction of the nine pulsars, and the inferred mean line-of-sight magnetic field strength of  $\sim 2 \mu\text{G}$  is about twice as large as the magnitude of the next largest value in this sample. Still, this is not anomalously high for Galactic values. An additional localized region of highly magnetized plasma between us and PSR J1301–6305 could be enhancing the RM, but there is no evidence for such a region in radio maps.

### 4. CONCLUSIONS

Using pulsar-gated radio interferometric observations taken at 1384 and 2496 MHz with the ATCA, we have measured the flux densities and polarization properties of two Vela-like pulsars, PSRs J0940–5428 and J1301–6305. The measured spectral indices for both pulsars from our observations are shallow but still consistent with values for the known pulsar population (Maron et al. 2000). The polarization properties of the pulsed emission indicate that both pulsars are highly polarized at both frequencies. The shallow spectral indices and the high degree of linear polarization are both consistent with the properties of other young, Vela-like radio pulsars, and these measurements fit a previously established correlation between spin-down luminosity and degree of linear polarization at 1400 MHz (von Hoensbroech et al. 1998; Crawford, Manchester, & Kaspi 2001). The RMs derived for the pulsars are consistent with measurements made at 1400 MHz using the Parkes telescope, and they yield mean line-of-sight magnetic field strengths that are within the normal range for Galactic values (Han et al. 2006).

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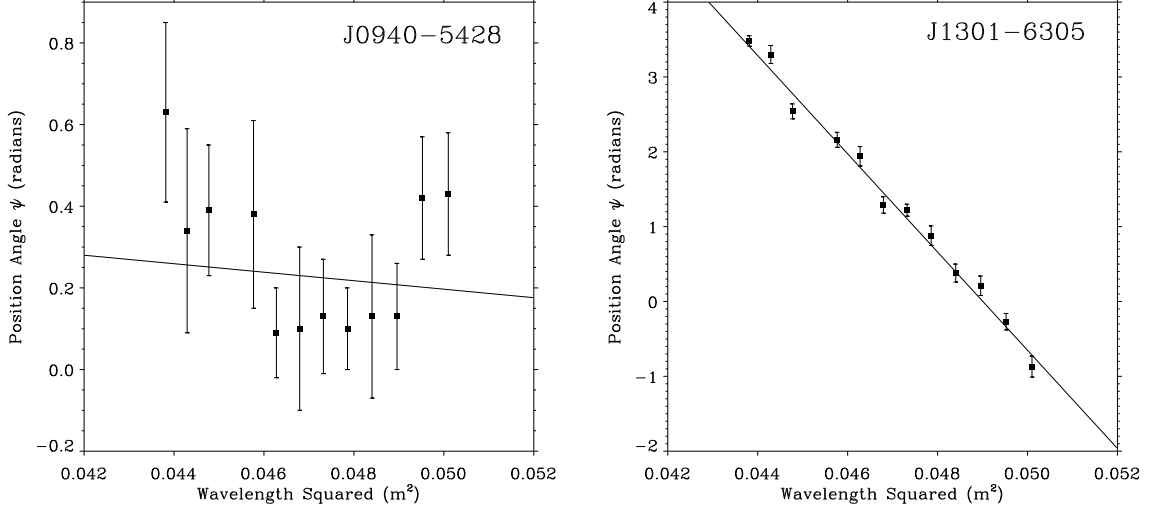


FIG. 1.— Position angle (PA) vs. wavelength squared for PSRs J0940-5428 (left) and J1301-6305 (right). Only the pulsed emission at 1384 MHz was used for each plot. Several frequency channels were excised from each data set during processing and are not used here. The best-fit linear function is overlaid, the slope of which is the measured RM (see Table 3). The best-fit y-intercepts are  $0.7 \pm 1.2$  rad for PSR J0940-5428 and  $2.8 \pm 0.7$  rad for PSR J1301-6305 (after an integer number of  $\pi$  phase winds are accounted for).

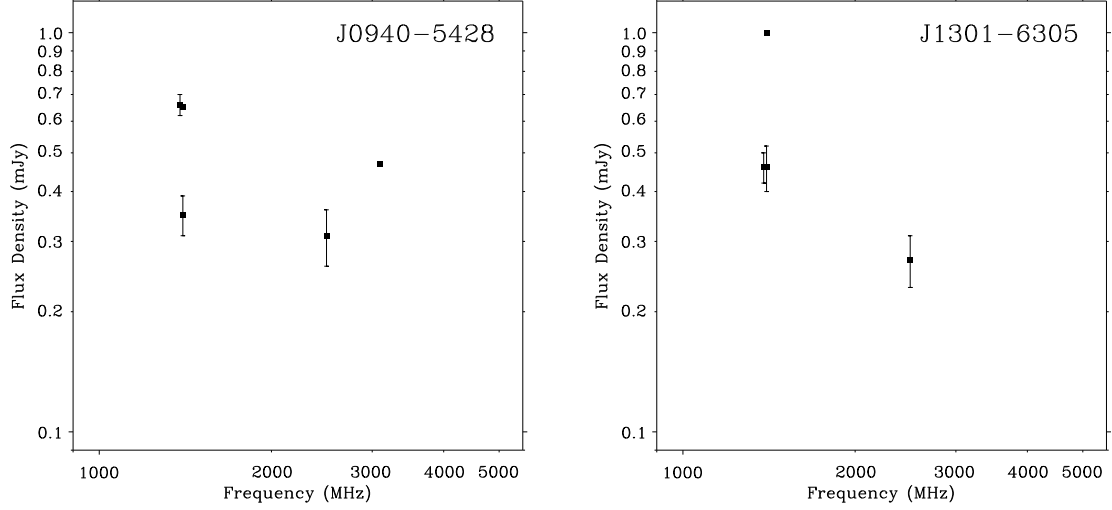


FIG. 2.— Flux density vs. frequency for PSRs J0940-5428 (left) and J1301-6305 (right). All measured points from Table 2 are included, with uncertainties shown where available. Both pulsars have shallow spectral indices relative to the mean value of the known radio pulsar population (Maron et al. 2000), but they are still within the expected range for young, Vela-like pulsars.

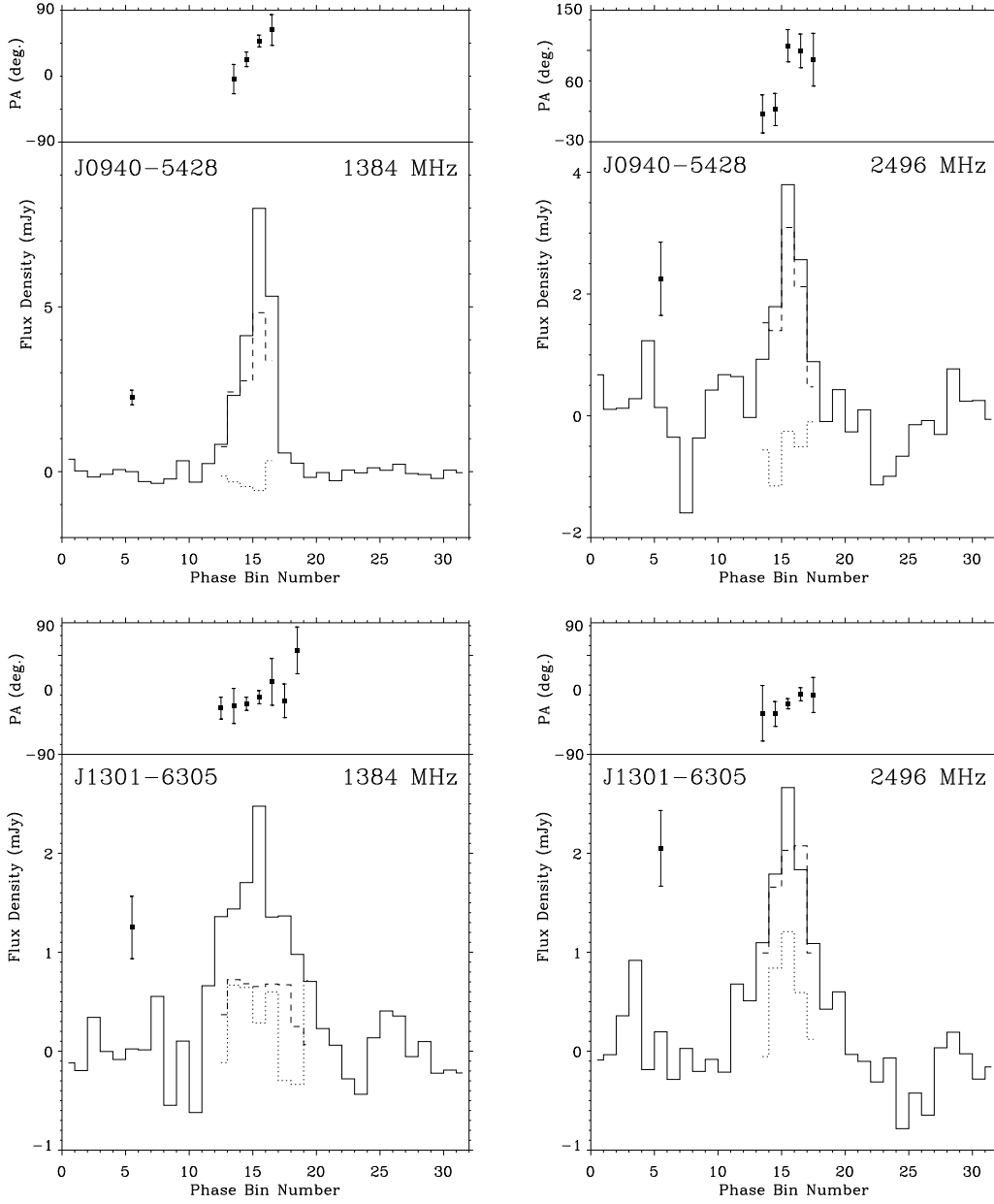


FIG. 3.— Polarization profiles for PSRs J0940–5428 (top row) and J1301–6305 (bottom row) at 1384 MHz (left) and 2496 MHz (right). Each profile has 32 phase bins and was created from data taken with the ATCA. One full period is shown for each profile. The off-pulse rms for each profile is indicated by the error bar to the left of the profile, and a mean off-pulse baseline value has been subtracted from all bins in each profile. Solid, dashed, and dotted lines indicate total intensity, linearly polarized intensity, and circularly polarized intensity, respectively. The PAs (measured from North to East) and their uncertainties are shown above each profile bin where measurements were possible. Bandwidth depolarization is not accounted for in the profiles, which, in the case of PSR J1301–6305 at 1384 MHz, significantly reduces the measured linear polarization fraction relative to its true value (see Table 3).

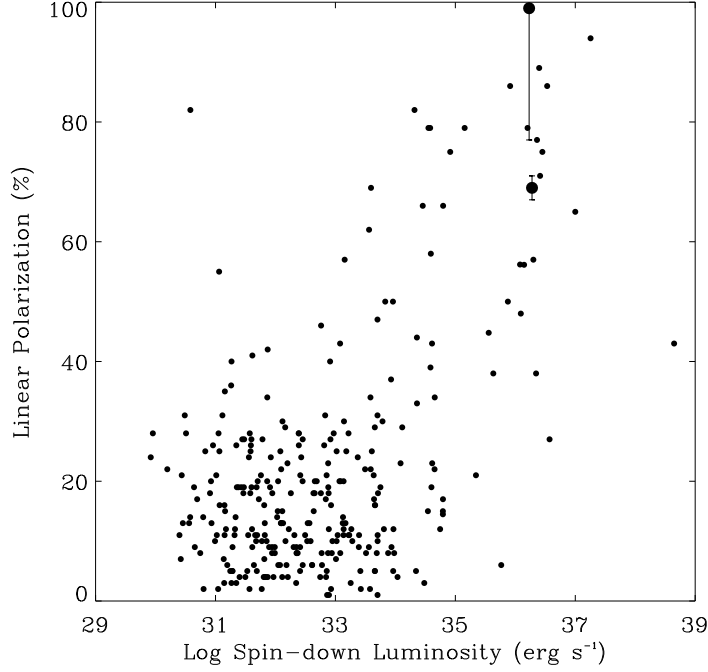


FIG. 4.— Fractional linear polarization at 1400 MHz vs. spin-down luminosity for pulsars with published 1400-MHz polarization measurements. This sample includes 278 pulsars published by Gould & Lyne (1998) and a number of measurements made at or near 1400 MHz published elsewhere (Qiao et al. 1995; Manchester & Johnston 1995; Crawford, Manchester, & Kaspi 2001; Roberts et al. 2001; Crawford & Keim 2003). This figure is an extension of Figure 2 shown by Crawford, Manchester, & Kaspi (2001). The two pulsars shown with  $1\sigma$  error bars are PSRs J0940-5428 and J1301-6305, measured using the ATCA at 1384 MHz. The linear polarization fraction for PSR J1301-6305 has been corrected for bandwidth depolarization and nears 100% at this frequency. These two pulsars fit a previously noted correlation between spin-down luminosity and degree of linear polarization at 1400 MHz.

TABLE 1  
ATCA OBSERVING PARAMETERS.

PSR	Observing Date	Array Config.	PKS Phase Calibrator	PKS Flux Calibrator	Integration Time (hr)
J0940–5428	1999 Aug 18	6D	0823–500	1934–638	6.8
J1301–6305	1999 Aug 22	6D	1329–665	1934–638	10.6

NOTE. — In both observations, data were taken at center frequencies of 1384 and 2496 MHz with 32 phase bins used in pulsar gating. A bandwidth of 128 MHz was used for each frequency in each observation, but this was reduced to 104 MHz after excision of some data during processing. The reduced bandwidth consisted of 13 contiguous 8-MHz channels.

TABLE 2  
FLUX DENSITIES AND SPECTRAL INDICES.

PSR	J0940–5428	J1301–6305
1384-MHz flux density (mJy) <sup>a</sup>	0.66(4)	0.46(4)
2496-MHz flux density (mJy) <sup>a</sup>	0.31(5)	0.27(4)
Spectral Index, $\alpha$ <sup>b</sup>	−1.3(3)	−0.9(3)
1400-MHz flux density (mJy) <sup>c</sup>	0.35(4)	0.46(6)
1400-MHz flux density (mJy) <sup>d</sup>	0.65	1.00
3100-MHz flux density (mJy) <sup>d</sup>	0.47	—

NOTE. — Figures in parentheses represent the  $1\sigma$  uncertainty in the least significant digit quoted.

<sup>a</sup>From ATCA gated data.

<sup>b</sup>Spectral index  $\alpha$  (defined according to  $S \sim \nu^\alpha$ ) determined using 1384 and 2496 MHz ATCA flux densities.

<sup>c</sup>From Parkes timing observations (Manchester et al. 2001).

<sup>d</sup>From Parkes polarization observations (Johnston & Weisberg 2006).

TABLE 3  
POLARIZATION CHARACTERISTICS.

PSR	J0940–5428		J1301–6305	
Frequency (MHz)	1384	2496	1384	2496
$\langle L \rangle / S$ (%) <sup>a</sup>	$69 \pm 2$	$86 \pm 14$	$99 \pm 22^f$	$94 \pm 10^f$
$\langle V \rangle / S$ (%) <sup>b</sup>	$-6 \pm 2$	$-26 \pm 14$	$+19 \pm 8$	$+32 \pm 10$
$\langle  V  \rangle / S$ (%) <sup>c</sup>	$9 \pm 2$	$26 \pm 14$	$32 \pm 8$	$33 \pm 10$
RM (rad m <sup>−2</sup> ) <sup>d</sup>	$-10 \pm 24$	—	$-631 \pm 15$	—
$\langle B_{\parallel} \rangle$ ( $\mu$ G) <sup>e</sup>	$-0.09 \pm 0.22$	—	$-2.08 \pm 0.05$	—

NOTE. — Listed uncertainties are at the  $1\sigma$  level, and all percentages have been rounded to the nearest whole number.

<sup>a</sup>Fractional on-pulse linear polarization.

<sup>b</sup>Fractional on-pulse circular polarization. Positive values correspond to left circular polarization.

<sup>c</sup>Fractional on-pulse absolute circular polarization.

<sup>d</sup>Rotation measure derived from the 1384-MHz ATCA data.

<sup>e</sup>Mean line-of-sight magnetic field strength. Negative values correspond to field lines pointing away from the observer.

<sup>f</sup>Values have been corrected for bandwidth depolarization using the measured RM and a bandwidth of 104 MHz. Values measured for PSR J1301–6305 prior to correction were  $35 \pm 8\%$  at 1384 MHz and  $91 \pm 10\%$  at 2496 MHz.